Modeling and Design of Multiwinding Magnetics for High Frequency Power Electronics

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We Need Better Magnetics

- Breakthroughs in semiconductor devices (SiC and GaN)

- Magnetics are lagging behind

Energy Density vs. Functionality

- Capacitors win in energy density
- Larger magnetics has better figure-of-merits
- Magnetics win in functionality
- **Multi-winding, multi-leg, multi-functional magnetics @ high frequency**

\[ VA \propto \epsilon^4 \]

Linear scaling factor

Source: Robert Pilawa

Source: Charles Sullivan
Multi-Functional Magnetics

Single Purpose Magnetics

Multiwinding Magnetics

Multileg Magnetics
The “integrated magnetics” concept started from 1980s’

Need tools and methods to design for high frequencies
Multi-Winding Magnetics: Two Categories

- Multiple windings couple to a single magnetic linkage

- Multiple windings couple to multiple magnetic linkages

1. What is the optimal way to interleave many layers?

- Alternating interleaved
- Symmetric interleaved
- More complicated?

2. What are the optimal winding stack and winding spacing?

- Thin Middle Spacing
- Thick Middle Spacing

3. Multi-object optimization problem

1) Interleaving options?
2) Materials?
3) Geometry?
4) Size?
5) Efficiency?
6) Coupling coefficient?
Two Commonly Shared Assumptions

Every model starts from assumptions …

(1) MQS assumption

- Assume $\frac{\partial E}{\partial t} = 0$.
- Applicable when the wavelength is much longer than the device size (usually lower than ~100MHz).

Magneto-Quasi-Static Maxwell’s equations

\[
\begin{align*}
\nabla E &= \frac{\rho}{\varepsilon_0} \\
\nabla B &= 0 \\
\n\nabla \times E &= -\frac{\partial B}{\partial t} \\
\n\nabla \times B &= \mu_0 (\mathbf{J} + \varepsilon_0 \frac{\partial E}{\partial t})
\end{align*}
\]

Ignore the time evolution of the electric field

(2) 1-D assumption

- Fields vary only along the thickness direction.
- Applicable when the flux is guided by the magnetic core.

Magnetic core guides the flux

Skin and proximity effects change current distribution
Wave Propagation in Planar Windings

- 1-D energy wave (Poynting vector) propagation principles

- Modular lumped circuit models for repeating building blocks
Modeling a Single Conductor Layer

Field diffusion equations:

\[ H_x(z) = \frac{H_T \sinh(\Psi z) + H_B \sinh(\Psi (h - z))}{\sinh(\Psi h)} \]

Ampere’s law:

\[ \nabla \times H = J = \sigma E \]

\[ \psi = \frac{1 + j}{\delta} \]
\[ \delta = \frac{2}{\mu \omega \sigma} \]

E field as a function of H and K:

\[ E_T = E_Y(h) = \frac{\psi}{\sigma} \frac{H_T e^{\Psi h} - H_B e^{-\Psi h}}{e^{\Psi h} - e^{-\Psi h}} \]
\[ E_B = E_Y(0) = \frac{\psi}{\sigma} \frac{H_T - H_B e^{-\Psi h} - H_B e^{\Psi h} - H_T}{e^{\Psi h} - e^{-\Psi h}} \]

\[ Z_a = \frac{\Psi(1 - e^{-\Psi h})}{\sigma(1 + e^{-\Psi h})} \]
\[ Z_b = \frac{2\Psi e^{-\Psi h}}{\sigma(1 - e^{-2\Psi h})} \]

KVL/KCL relationships:

\[ \frac{V}{m} \quad \Omega \quad \frac{A}{m} \]

\[ \begin{cases} E_T = Z_a H_T + Z_b K & \text{KVL} \\ E_B = Z_b K - Z_a H_B & \text{KVL} \\ K = H_T - H_B & \text{KCL} \end{cases} \]

Electromagnetic Fields

KVL

H & K: through variables ~ unit (A/m)

E: across variable ~ unit (V/m)

Z_a, Z_b: impedances ~ unit (\(\Omega\))
Modeling Two Adjacent Layers

Intuition:

- Two three-terminal networks
- Connected by the $H$ field between them

Faraday’s Law and Field Continuity

$$E_{B1}d - V_1 = -\frac{d\Phi_{B1}}{dt} \quad E_{T2}d - V_2 = -\frac{d\Phi_{T2}}{dt}$$

$$\frac{d\Phi_{T2}}{dt} = \frac{d\Phi_{B1}}{dt} + \frac{d\Phi_A}{dt}$$

Flux Linking Two Layers:

An additional KVL equation

$$j\omega\mu_0 a_1 \frac{H_{S12}}{\Omega} = \frac{V_2}{d} - \frac{E_{T2}}{d} - \frac{V_1}{d} + E_{B1}$$

$A/m$ $V/m$
Fields distributions in multiple-turns layers are linearly related to those in single-turn layers

**Multiple turns → Additional Linear Conversions**

**E&M Domain**

**Circuit Domain**

Intuitive Ideal Transformers
Modeling Electrical Interconnects (Vias)

Modeling vias is equivalent to adding KVL, KCL constraints:

Layer $i$ and Layer $j$ in series
Layer $k$ and Layer $l$ in parallel

\[
\begin{align*}
V_i + V_j &= V_a \\
V_k &= V_l = V_b \\
I_i &= I_j = I_a \\
I_k + I_l &= I_b
\end{align*}
\]

Connect the layer ports in the same pattern as they are in the real circuit.

Series Layers
Parallel Layers
An Open-Source SPICE Modeling Tool

1. Geometry Information
   - Magnetic Core
   - Winding stack
   - Side air gap
   - Center air gap
   - Side air gap

2. Modular Layer Model
   - Top Side of the Core
   - Spacing
   - Layer 1
   - Spacing
   - Layer 2
   - Spacing
   - Layer 3
   - Spacing
   - Layer ...
   - Spacing
   - Bottom Side of the Core
   - 5:1 Series Vias
   - 1:1 Parallel Vias

3. SPICE Netlist
   - Circuit Domain
   - E&M Domain
   - Layer 1
   - Layer 2
   - Layer 3
   - Layer 4
   - Winding a
   - Winding b
   - Winding ports
   - Spacing
   - M:2SPICE

Simulations!

Search: M2SPICE
Impacts of Interleaving Patterns

Comparing the $P_{ac}$ and $E_{ac}$ of three 1:1 transformers with three different interleaving patterns

\[ P_{ac} = \sum I^2 R_{ac} \]

\[ E_{ac} = \frac{1}{2} \sum I^2 L_{ac} \]

Interleaving has to be done in the right way !!!
Example Applications

Multi-Input Multi-Output Power Electronics Systems

Battery Banks  Server Racks  Solar Farms
Power Management for Storage Servers

Magnetics Design  Circuit Topology  System Integration

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A Conventional Dc-Dc Approach

Hard Drive Data Storage Server

100% Power Processing

50V

5V

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Differential Power Processing

DC Bus

Domain 1
- HDD 1.1
- HDD 1.2
- HDD 1.3
- HDD 1.M

Domain 2
- HDD 2.1
- HDD 2.2
- HDD 2.3
- HDD 2.M

Domain 3
- HDD 3.1
- HDD 3.2
- HDD 3.3
- HDD 3.M

Domain N
- HDD N.1
- HDD N.2
- HDD N.3
- HDD N.M

DPP Converter

Differential Power Processing

50V
45V
40V
5V
GND

<10% Differential Power
Existing DPP Solutions

DPP with a buffer port

Ladder DPP


Transformer saturation requirements: maximum volt-seconds per turn

\[ \frac{V_1}{N_1} = \frac{d\Phi_1}{dt} \]
\[ \frac{V_2}{N_2} = \frac{d\Phi_2}{dt} \]
\[ \vdots \]
\[ \frac{V_n}{N_n} = \frac{d\Phi_n}{dt} \]

3D stacked multiwinding transformer with modular planar modeling

PCB1: Layer 1 – Layer 6

PCB2: Layer 7 – Layer 10
Distributed Phase Shift Control

Phase shift determines the power flow

\[ V_{1/N_1} \]
\[ V_{2/N_2} \]
\[ V_{3/N_3} \]
\[ I_{12} \]

Block diagram of the distributed control
Complete HDD Storage System

HDD Array

MotherBoard

Power Supply

MAC-DPP
Performance of the DPP Architecture

Summary:
- Multiwinding transformer enables ultra high performance DPP
- DPP architecture fits well to large scale modular systems
MIMO Reconfigurable Energy Router

Series-Parallel Reconfigurable

Lumped Circuit Model for Magnetics

- Multiple winding coupled to a single flux linkage

- Multiple windings coupled to multiple flux linkages

**electrical circuit model**

**reluctance circuit model**

Inverse
Circuit Models for Coupled Magnetics

Physical Structure

Reluctance Model

Multiwinding Transformer Model

Inductance Matrix Model
Permeance Model & Reluctance Model

Advantage of the Permeance Model

- Simple
- Intuitive
- No coupled inductors
- Explicit design equations
- Capability of capturing core loss

Permeance Model for SPICE Simulation

Multileg Coupled Magnetics

Topological duality

D. Zhou et al., “Permeance Model for Programmable Multiphase Coupled Magnetics”, COMPEL20, submitted
Hybrid Converter with Coupled Magnetics

Towards a MIMO Magnetic Energy Processor
A Magnetic Memory in 1960s

- A 32 x 32 core memory storing 1024 bits of data
- Instead of processing information, we process energy
Exciting Opportunities for Power Electronics & Magnetics

Information Processing

Energy Processing

32 x 32 Magnetic Memory

10-Port MIMO Power Converter

More topologies and designs to be investigated!
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References

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